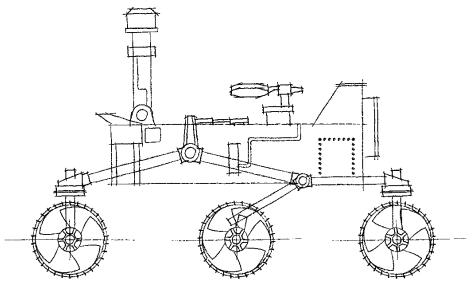# Mars 2020 Terrain Relative Navigation Verification & Validation

Aaron Stehura

Paul Brugarolas, Allen Chen, Andrew Johnson, Swati Mohan, Jim Montgomery

14th International Planetary Probe Workshop

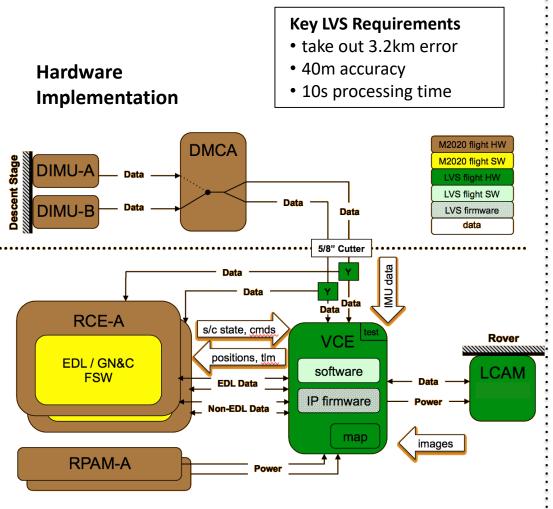The Hague, Netherlands

June 13th, 2017

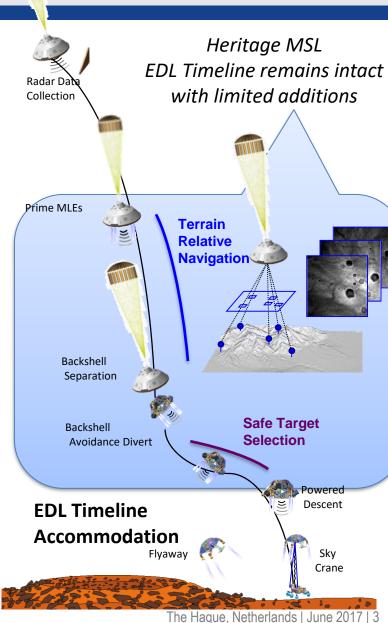**Mars 2020** Project

Summary

- TRN: a new, enabling sensor for Mars 2020

- V&V philosophy: trifecta approach
  - Hardware testing
  - Field testing
  - Simulation & analysis

- V&V in practice
  - Key paradigm: hardware delivery & model certification pave the way for high fidelity simulation

- Current status

TRN Overview

Key LVS Requirements
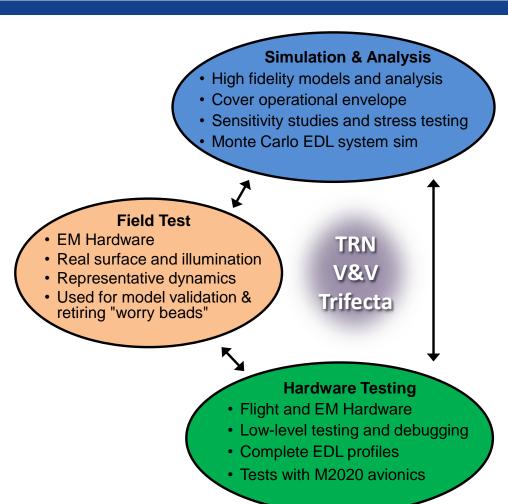- take out 3.2km error
- 40m accuracy
- 10s processing time

Hardware Implementation

Heritage MSL EDL Timeline remains intact with limited additions

TRN is loosely coupled to the rest of the EDL system

EDL Timeline Accommodation

TRN Verification Activities Approach

Simulation & Analysis
- High fidelity models and analysis
- Cover operational envelope
- Sensitivity studies and stress testing
- Monte Carlo EDL system sim

Field Test
- EM Hardware
- Real surface and illumination
- Representative dynamics
- Used for model validation & retiring "worry beads"

TRN V&V Trifecta

Hardware Testing
- Flight and EM Hardware
- Low-level testing and debugging
- Complete EDL profiles
- Tests with M2020 avionics

- MSL landing radar (TDS) V&V program used same "Trifecta" approach

- Testing spans multiple dimensions
  - Test As You Fly
  - Stress Testing – expand the envelope
  - Worry Beads – sensitivity studies

- Each V&V venue has a different degree of hardware and software fidelity
  - All contain EDL/GNC FSW Core
  - Some contain modeled components: VCE, LCAM, DIMU
  - LVS: simple behavioral model, high fidelity simulation, or flight HWIL

- Validation
  - Field tests
  - Multiple Mars datasets
  - HWIL testing w/ spacecraft

TRN V&V Trifecta Coverage
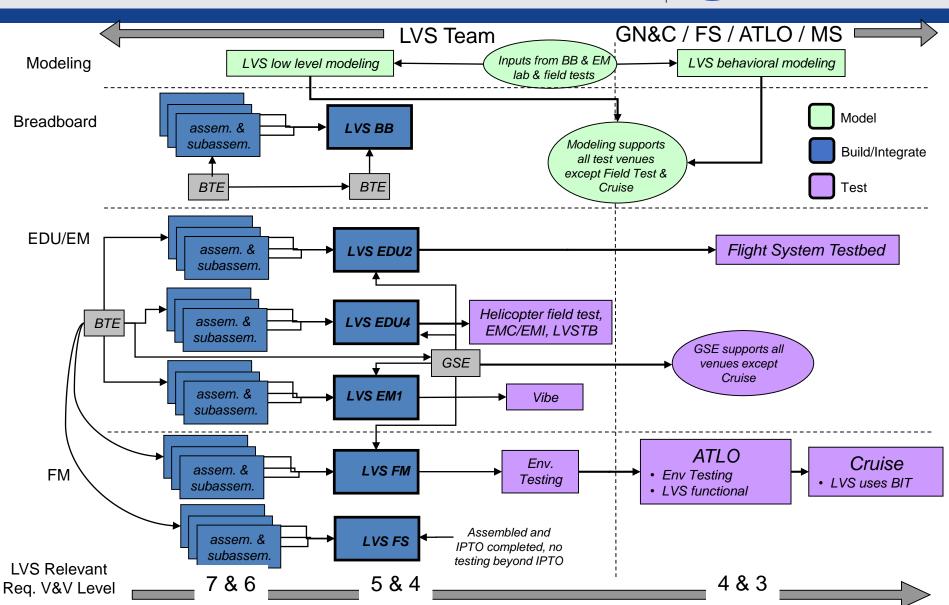
Jet Propulsion Laboratory
California Institute of Technology

V&V Trifecta covers all key environmental and performance parameters, just not at the same time

Full Coverage / Conditions Met | Partial Coverage | No Coverage / Conditions Not Met

		Priority	Field Tests — Captive Carry	Field Tests — Controlled Descent System	Simulations & Analysis	Hardware Testing
Terrain	Real world imaging response	high				
	Relief (up to 50 m)	high	Mars Analogs	Limited	Mars & Earth DEMs	Mars & Earth DEMs
	Slopes (up to 16 deg)	medium	Mars Analogs	Limited	Mars & Earth DEMs	Mars & Earth DEMs
	Albedo Variation (image entropy 3.0 to 7.5)	high	Mars Analogs	Limited	Mars & Earth imagery	Mars & Earth imagery
	Illumination (sun elevation 25 deg to 55 deg)	high				
Flight Profiles, Trajectories, and Dynamics	TRN altitude range (2.0 km to 4.2 km AGL)	high		Limited		
	Vertical Velocity (50 m/s to 115 m/s)	high	up to 5 m/s			
	Horizontal Velocity (up to 70 m/s)	low		Limited		
	Off-nadir attitude (up to 45 deg)	high		Limited		
	Attitude rates (up to 50 deg/s)	low		Limited		
	# of runs	-	Thousands	Tens	Many many thousands	Thousands
Hardware	Hardware pedigree	-	EM	EM	N/A	BB, EM, & Flight
	Integration with MSL avionics	-			N/A	
	Closed-loop with GN&C	-				
System	Low-level functional insight (standalone)	-				
	Integrated functional insight (system-level)	-			Limited	
	Piecewise integration and physics	-				
	High fidelity integration, physics, and flight profiles in one venue	-				

LVS Integration & Test Flow

LVS Team — GN&C / FS / ATLO / MS

Modeling

LVS low level modeling ← Inputs from BB & EM lab & field tests → LVS behavioral modeling

Legend:
- Model
- Build/Integrate
- Test

Breadboard

assem. & subassem. → LVS BB

BTE — BTE

Modeling supports all test venues except Field Test & Cruise

EDU/EM

assem. & subassem. → LVS EDU2 → Flight System Testbed

BTE

assem. & subassem. → LVS EDU4 → Helicopter field test, EMC/EMI, LVSTB

GSE → GSE supports all venues except Cruise

assem. & subassem. → LVS EM1 → Vibe

FM

assem. & subassem. → LVS FM → Env. Testing → **ATLO**
- Env Testing
- LVS functional
→ **Cruise**
- LVS uses BIT

assem. & subassem. → LVS FS ← Assembled and IPTO completed, no testing beyond IPTO

LVS Relevant Req. V&V Level

7 & 6   5 & 4   4 & 3

LVS Field Testing

Helicopter, Captive Carry
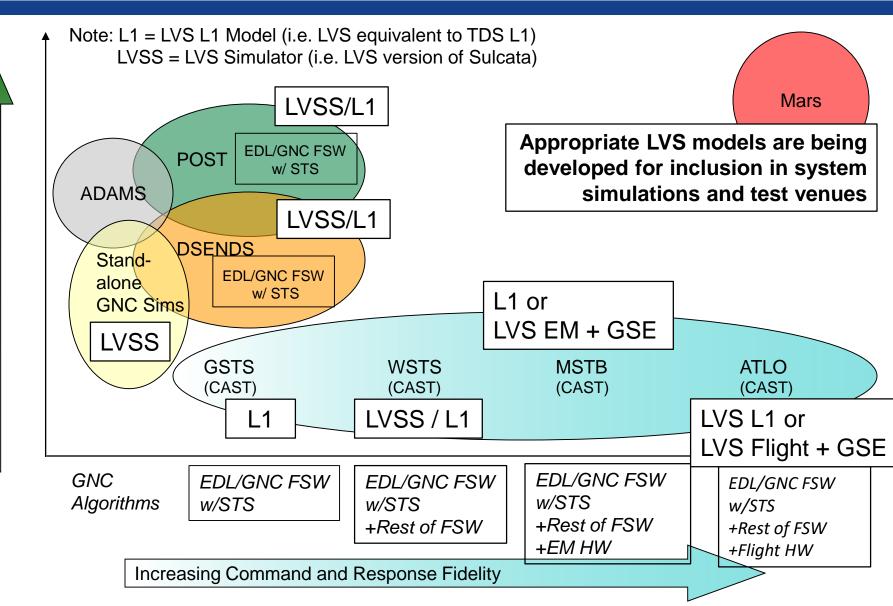
Helicopter, Captive Carry (Prototype Field Test, 2014)

Helicopter, Controlled Descent System

- Key elements of field testing
  - Realtime operation of EM system over operational envelope
  - Gathering flight-like data sets, including coordinated image, IMU, and GPS truth data → model validation
- Helicopter, Captive Carry
  - Meets all test requirements except for vertical descent velocity with lowest cost and risk
  - This platform was used to successfully verify performance of the LVS Prototype system
- Helicopter, Controlled Descent System
  - Provides increased vertical descent velocity
  - Descoped…further study determined LVS is not susceptible to high vertical velocities and physics involved is covered by other means
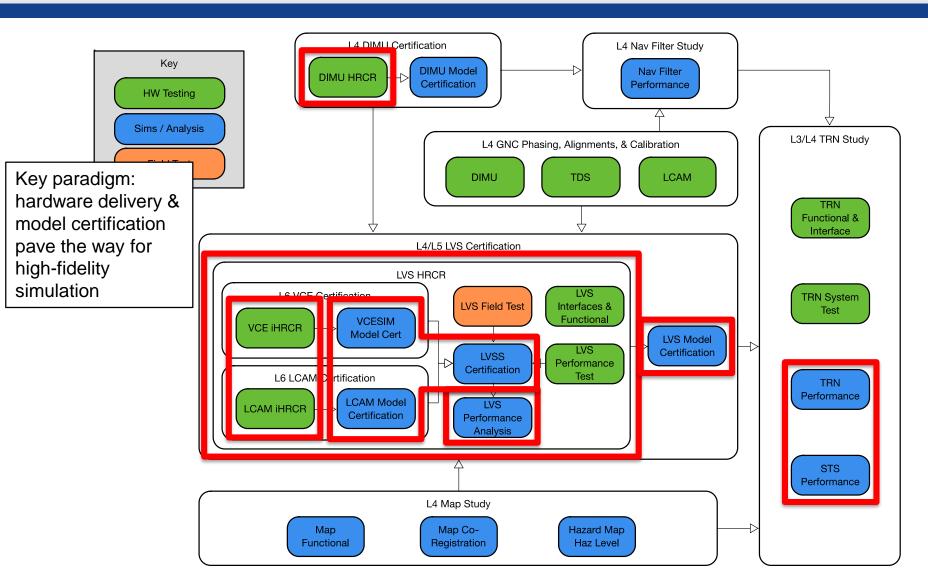
Simulation & Analysis

Note: L1 = LVS L1 Model (i.e. LVS equivalent to TDS L1)
LVSS = LVS Simulator (i.e. LVS version of Sulcata)

Increasing Flight Dynamics Fidelity

Mars

LVSS/L1

POST

ADAMS

EDL/GNC FSW w/ STS

Appropriate LVS models are being developed for inclusion in system simulations and test venues

LVSS/L1

DSENDS

Stand-alone GNC Sims

EDL/GNC FSW w/ STS

LVSS

L1 or
LVS EM + GSE

GSTS (CAST)	WSTS (CAST)	MSTB (CAST)	ATLO (CAST)
L1	LVSS / L1		

LVS L1 or
LVS Flight + GSE

GNC Algorithms	EDL/GNC FSW w/STS	EDL/GNC FSW w/STS +Rest of FSW	EDL/GNC FSW w/STS +Rest of FSW +EM HW	EDL/GNC FSW w/STS +Rest of FSW +Flight HW

Increasing Command and Response Fidelity

L3-L5 V&V Relationships

Key
- HW Testing
- Sims / Analysis
- Field Test

Key paradigm: hardware delivery & model certification pave the way for high-fidelity simulation

L4 DIMU Certification
- DIMU HRCR → DIMU Model Certification

L4 Nav Filter Study
- Nav Filter Performance

L4 GNC Phasing, Alignments, & Calibration
- DIMU
- TDS
- LCAM

L3/L4 TRN Study
- TRN Functional & Interface
- TRN System Test
- TRN Performance
- STS Performance

L4/L5 LVS Certification

LVS HRCR
- LVS Field Test
- LVS Interfaces & Functional
- LVS Performance Test
- LVS Model Certification

L6 VCE Certification
- VCE iHRCR → VCESIM Model Cert

L6 LCAM Certification
- LCAM iHRCR → LCAM Model Certification

- LVSS Certification
- LVS Performance Analysis

L4 Map Study
- Map Functional
- Map Co-Registration
- Hazard Map Haz Level

Current Status

- TRN: a new, enabling sensor for Mars 2020 | CDR end of FY '17 |

- V&V philosophy: trifecta approach
  - Hardware testing | EDU & GSE builds in progress |
  - Field testing | Planned for April/May '18 |
  - Simulation & analysis | LVS L1 integrated in EDL system simulation
    LVSS high fidelity simulation running standalone |

- V&V in practice
  - Key paradigm: hardware delivery & model certification pave the way for high fidelity simulation

- Current status | Primary risk is schedule |

Related Material

- Allen Chen et al. (2016) *Mars 2020 Entry, Descent, and Landing System Overview*, IPPW13 Presentation.
- Aaron Stehura et al. (2015) *The Future of Landing: Terrain Relative Navigation From Prototype to Mars 2020*, IPPW12 Presentation.
- Paul Brugarolas et al. (2016) *On-Board Terrain Relative Safe Target Selection for the M2020 Mission*, IPPW13 Presentation.
- James Montgomery et al. (2016) *The Mars 2020 Lander Vision System*, IPPW13 Presentation.
- Aaron Stehura et al. (2016) *Mars 2020 Terrain Relative Navigation Accommodation*, IPPW13 Poster.
- Andrew Johnson et al. *Design and Analysis of Map Relative Localization for Access to Hazardous Landing Sites on Mars*, AIAA Guidance, Navigation, and Control Conference, AIAA SciTech Forum, (AIAA 2016-0379).
- Andrew E. Johnson et al. *Real-Time Terrain Relative Navigation Test Results from a Relevant Environment for Mars Landing*, AIAA Guidance, Navigation, and Control Conference, AIAA SciTech Forum, (AIAA 2015-0851).

BACKUP

Key Acronyms

- BB — breadboard
- CC — captive carry
- CEPCU — compute element power conditioning unit
- CDS — controlled descent system
- CVAC — computer vision accelerator card
- DEM — digital elevation map
- DIMU — descent inertial measurement unit
- DMCA — descent motor control assembly
- EDL — entry, descent, and landing
- EDU — engineering development unit
- EM — engineering model
- EMC — electromagnetic compatibility
- EMI — electromagnetic interference
- GN&C — guidance, navigation and control
- GSE — ground support equipment

- HRCR — hardware review certification record
- HWIL — hardware-in-the-loop
- IP — image processing
- LCAM — LVS camera
- LVS — lander vision system
- LVSS — LVS simulation
- LVSTB — LVS testbed
- R4R — run for record
- RCE — rover compute element
- RPAM — rover power and analog module
- PF — protoflight
- STM — safe-to-mate
- STS — safe target selection
- TDS — terminal descent sensor
- TRN — terrain relative navigation
- TVAC — thermal vacuum
- VCE — vision compute element
- V&V — verification and validation

Terminology

- TRN = Terrain Relative Navigation
  - All the new development to avoid known hazards in the landing ellipse
- STS = Safe Target Selection
  - Picks the safe landing site between a-priori hazards based on the position provided by LVS
- LVS = Lander Vision System
  - The system that performs Map Relative Localization
- MRL = Map Relative Localization
  - The algorithms that compute position relative to a map

```
TRN
 ├── STS
 └── LVS
      ├── MRL
      ├── VCE
      │    ├── RAD750
      │    ├── CVAC
      │    │    ├── HK
      │    │    └── VP-E
      │    └── CEPCU1
      ├── VCEFSWE
      └── LCAM
```

- VCE = Vision Compute Element
  - The LVS processor containing three cards
- RAD750 = processor card
- CVAC = Computer Vision Accelerator Card
  - HK = Housekeeping FPGA on CVAC
  - VP-E = re-programmable Virtex5 FPGA on CVAC with sensor interfaces and image processing
- CEPCU1 = power conditioning card
- VCEFSWE = VCE Flight Software for EDL
- LCAM = LVS Camera, procured from MSSS

Comparison to TDS V&V

- ## TRN follows the TDS/GN&C V&V example for LVS
  - Similar trifecta (Field Testing, Simulation, Hardware Testing)
  - Similar separation between detailed, low level modeling and behavioral modeling
  - Similar types of tests (interface tests, calibration tests, simulated descents, functional tests, etc.)

LVS

| Full Coverage / Conditions Met | Partial Coverage | No Coverage / Conditions Not Met |

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	Integration with MSL avionics	-			N/A	
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	Integrated functional insight (system-level)	-			Limited	
	Piecewise integration and physics	-				
	High fidelity integration, physics, and flight profiles in one venue	-				

TDS

		Field Test	TDS Simulations	TDS Support Equipment
Terrain	Real-world terrain morphology	Yes	No	No
	Real-world backscatter	Yes	Earth DEMs	Earth DEMs
	Mars-like terrain morphology	Earth analogs	Mars DEMs	Mars DEMs
	Mars-like backscatter	Earth analogs	Yes, with model tools	Limited, Signal Attenuation
Flight Dynamics	EDL profiles/trajectories	TAYF to extent possible	Complete	Complete
	# runs/coverage	Limited	Very large, esp POST	Large
Hardware	Hardware pedigree	EM	none	EM & flight
	Integration with MSL avionics	No	Limited, No 1553 transactions	Yes
	Closed-loop with GN&C	No	Yes	Yes
System	Low-level functional insight	No	Yes, with model tools	Yes, with BTE
	Integrated functional insight	Yes	Limited	Yes, with EGSE
	Piecewise integration and physics	Yes		
	High fidelity integration, physics, and flight profiles in one venue	No	No	No

Model Certification Process

	Model Functional Definition	*Model Validation (Physics)*	*Model Verification (Mathematics)*	*Plug-In Verification*
Objectives	• Define functionality • Define required fidelity, if possible • Define fidelity for each user • Define I/O & ranges, format, units, etc. • Define governing equations and/or model validation data • List assumptions and applicability limits • Define test cases	• Review intended use/applicability of mathematical description • Validate that provided mathematical description accurately represents reality (to the degree we care) • Review block diagram for functionality	• Verify standalone model implemented accurately captures mathematical description • Review intended use/applicability of model • Verify required functionality (out of range flags, etc.)	• Verify model incorporated into simulation correctly • Verify user understanding of applicability of model • Verify required functions work when plugged in larger sim
Participants	• Provider • Modeler • Users • EDL Systems	• Provider • Modeler • Independent Subject Matter Expert • EDL Systems	• Provider • Modeler • Modeler peer • EDL Systems	• Modeler • User • User peer • EDL Systems

- Certification cycle repeated as needed with increasingly detailed input data for model refinement
- Steps may be combined where applicable
- Formality more important when users, modelers, and providers are organizationally or geographically dispersed
- Certification is sum of steps